Range Image Registration: A Software Platform and Empirical Evaluation

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Abstract

Building 3D models of real-world objects by assembling views taken by a range sensor promises to be a more efficient method than manually producing CAD drawings. In this technique, a series of range images are acquired and then registered, or aligned, with each other to a high degree of accuracy. Finally, the polygonal meshes corresponding to the range images are merged to form a complete 3D model consisting of a single mesh.

Many techniques have been proposed to solve the registration problem; however, little work has been done to date to compare several registration algorithms with the same sets of data. In this work, we examine a software test-bed built for performing such comparisons. Within this test-bed, we have implemented several common registration algorithm variants to the baseline *Iterative Closest Point (ICP)* algorithm and tested them on partially overlapping range images taken from four different objects.

Techniques Implemented

ICP Objective:
Align two surfaces by iteratively finding the rigid transformation that minimizes

$$f(\mathbf{R},\mathbf{T}) = \frac{\sum_{i=1}^{N_p} w_i \left\| x_i - \mathbf{R}p_i - \mathbf{T} \right\|^2}{\sum_{i=1}^{N_p} w_i}$$

where w_i is typically given by

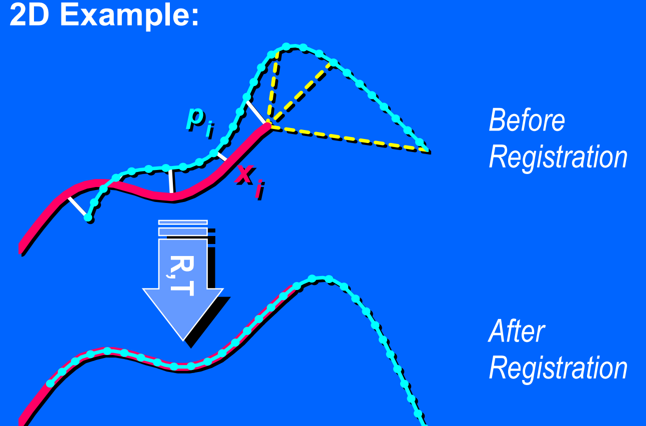
$$w_i = \begin{cases} 1 & \left\| x_i - p_i \right\|^2 < D_{max}{}^2 \\ 0 & else \end{cases}$$

for some maximum allowed point pair distance, D_{max}.

Algorithm Pseudo-Code:

Repeat
  Find corresponding point pairs, $\{(p_i, x_i)\}$
  Assign weights to each pair, $\{w_i\}$
  Compute the optimal transformation to minimize $f(\mathbf{R},\mathbf{T})$
Until $f(\mathbf{R},\mathbf{T})$ ceases to change significantly

2D Example:



P, the cyan curve, is being registered to X, the red curve. Thin solid **white** lines connect corresponding point pairs. Thin dashed **yellow** lines represent outlier pairs.

Schütz's Outlier Classifier

$D_{max} = (c \cdot s \cdot r)$

where $s \cdot r$ is the typical Euclidian distance between neighboring samples, and c is a dynamic tuning parameter that is decreased as the two surfaces become closer.

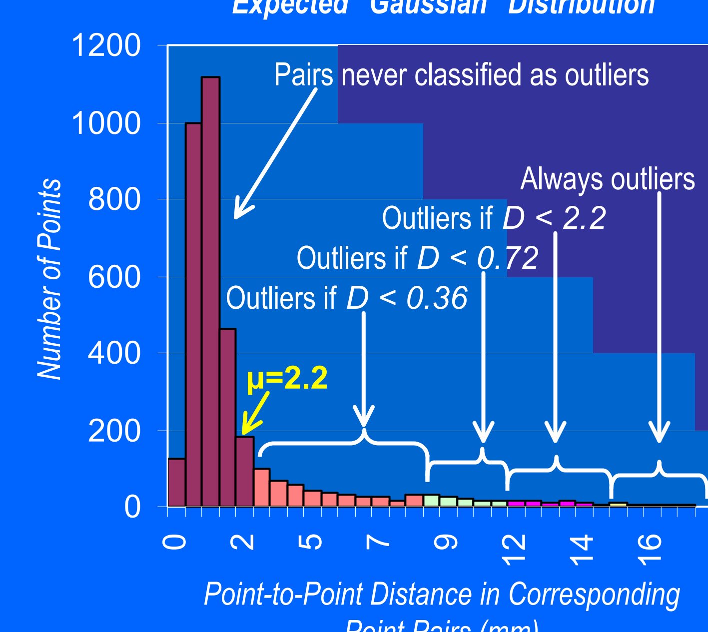
Zhang's Outlier Classifier

if $\mu < D$
  $D_{max} = \mu + 3\sigma$ (Registration is quite good)
elseif $\mu < 3D$
  $D_{max} = \mu + 2\sigma$ (Registration is still good)
elseif $\mu < 6D$
  $D_{max} = \mu + \sigma$ (Registration is not too bad)
else
  $D_{max} = \xi$ (Registration is really bad)

where ξ is the first valley after the largest peak in the histogram of the corresponding point pair distances.

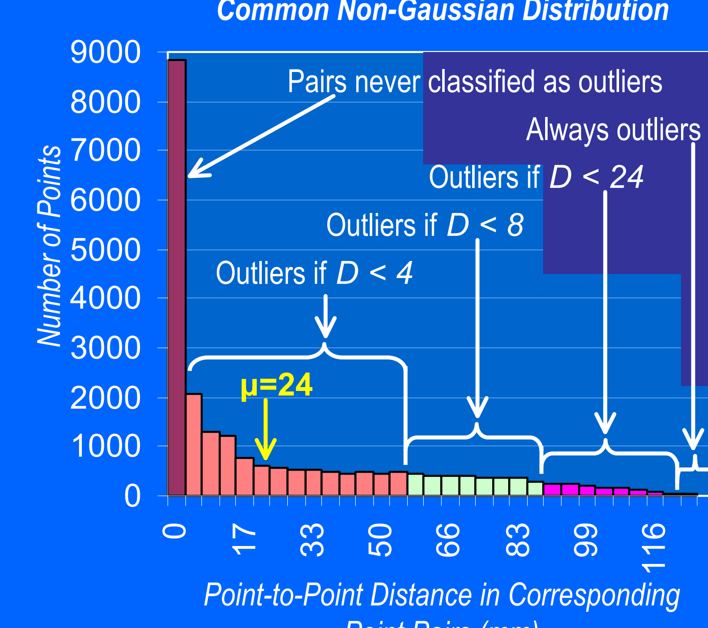
Sample Histograms of Corresponding Point Pair Distances

Expected "Gaussian" Distribution



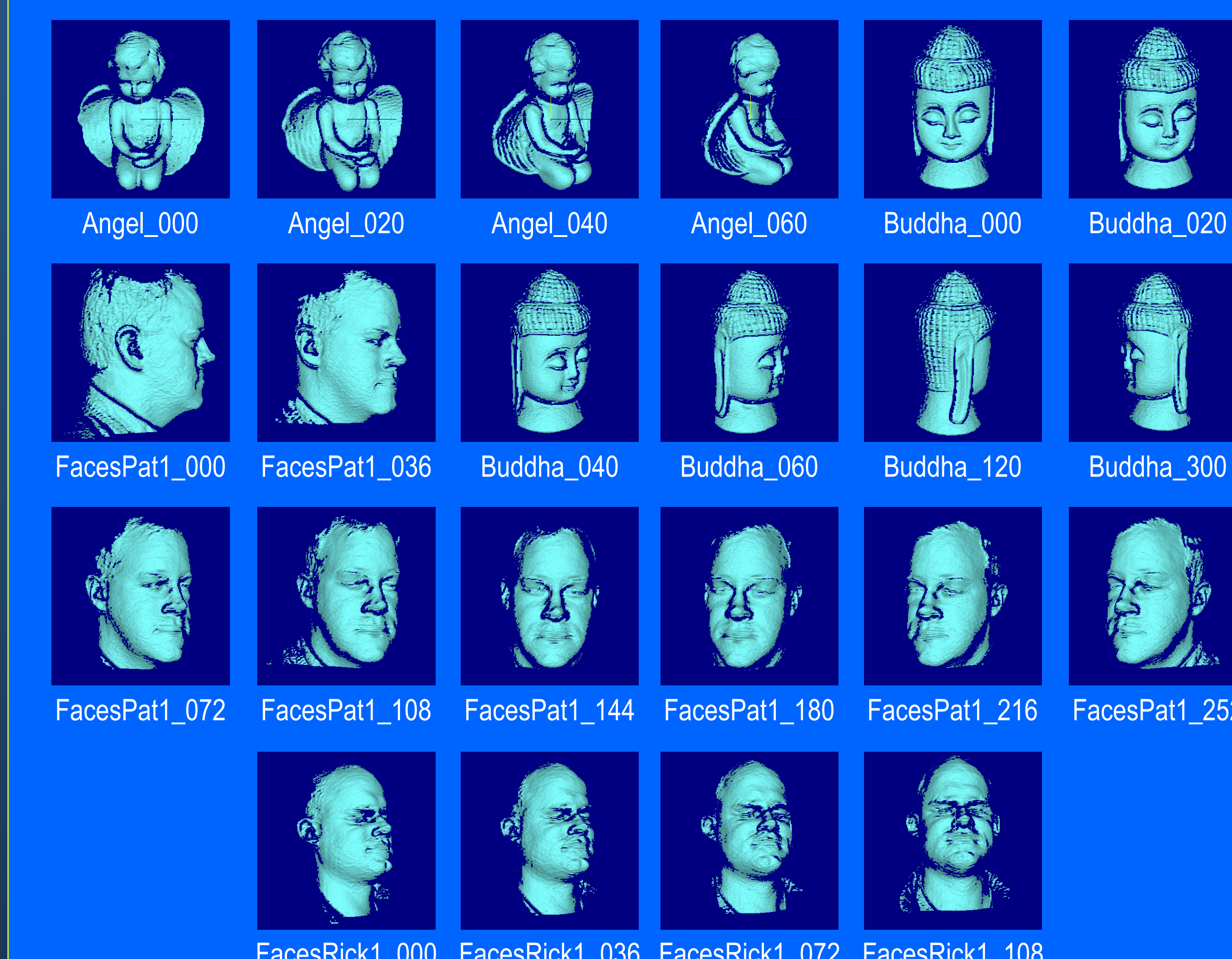
Point-to-Point Distance in Corresponding Point Pairs (mm)

Common Non-Gaussian Distribution



Point-to-Point Distance in Corresponding Point Pairs (mm)

Range Images Evaluated



Parameter Settings and Results

Uniform Decimation Factor

Factors used:

- 1, **2**, 4, 8, 16, and 32

Results:

- Factors greater than 2 produce noticeably worse registration results.

Loop Criterion

Criteria used:

- 0.3, 0.03, and **0.003**mm

Results:

- Tighter thresholds require more iterations and produce better results.

(Baseline parameter values given in ***bold****)*

Outlier Classifier

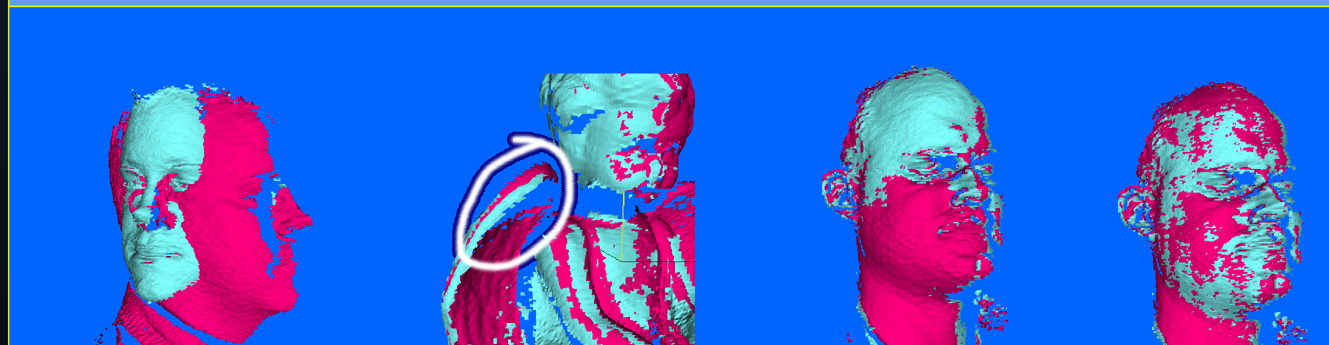
Parameter values (D and $s*r$):

- 7.1, **3.6**, 1.8, 0.9, 0.4, 0.2, and 0.1mm

Results by classifier type:

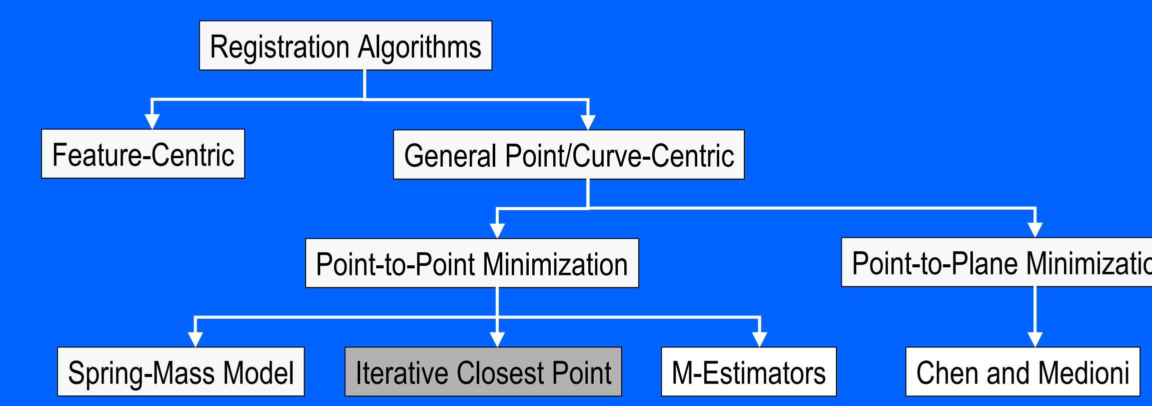
- **None**
  Catastrophic failure when significant non-overlapping regions exist.
- **Schütz's**
  Avoids catastrophic failures with proper parameter settings.
- **Zhang's**
  Typically yields the best results. Often works best when D is set so low that the $D_{max}=\xi$ condition is always selected.

Classification of Output

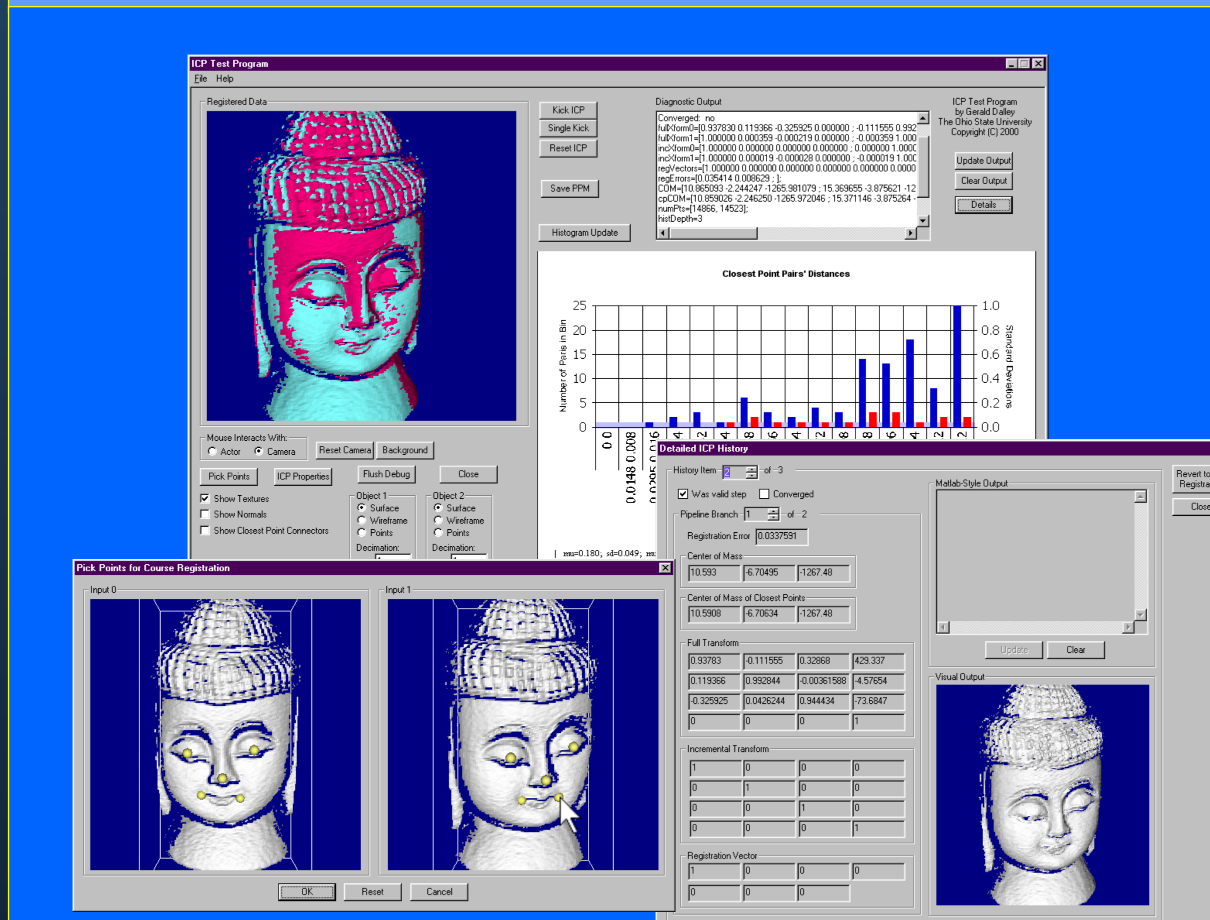


Catastrophic Failure | Misregistration at Regions of High Curvature | Poor "Splotching" | Good "Splotching"

Partial Taxonomy of Common Registration Techniques



Testbed GUI



These images are screenshots of the GUI implemented to configure the tests and evaluate the results.

Future Work

- Test alternate registration algorithms
  - Chen and Medioni's *(in progress)*
  - M-Estimators
  - ICP with point-to-interpolated point correspondence
  - Iterative Spring-Mass Systems
- Perform ground-truth tests *(in progress)*
- Evaluate effects of non-uniform decimation
- Perform registration with non-sphere topological objects
- Extend the software testbed

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